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DIASTROPHISM AND THE FORMATIVE PROCESSES. III

THE LATERAL STRESSES WITHIN THE CONTINENTAL PROTUBERANCES AND THEIR RELATIONS TO CONTINENTAL CREEP AND SEA-TRANSGRESSION

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In the second article of this series—preceding number of this *Journal*, pp. 517–33—it was urged that ordinary diastrophism springing from internal stresses is, in its very nature, unsuited to adjust the surface of the earth to the surface of the sea over wide areas with such close nicety as effectively to facilitate the great sea-transgressions and the formation of the great terranes of marine sediments that spring from them. This inadaptability is held to arise chiefly from the fact that the deforming earth-stresses, on the one hand, and the working relations of the sea-surface to the sea-shelves, on the other, are so far independent of one another in origin and mode of action that they are not naturally co-operative in so close and harmonious a way as to be suited to produce the observed results, since these are obviously the effects of nicely adjusted relations.

So, too, it appeared that such vertical stresses as may arise from loading and unloading in the process of gradation are unsuited to produce these results, because loading and unloading tend to produce a warp between the loaded and the unloaded tracts,

whereas great sea-transgressions and great terranes of parallel sediments require either a movement that retains the parallelism of the sea-surface and the sea-bottom, or else the essential absence of any movement at all. A constant upwarping of the land inevitably defeats extensive sea-transgression and its consequent terranes.

In further pursuing the conditions that favor or oppose great sea-transgression and the formation of the great parallel terranes of marine strata, we have now to consider the unbalanced stresses that inevitably arise *within* the continents as a consequence of their own protrusions. These are to be distinguished from the internal stresses of a more general nature that are usually regarded as the cause of orogenic and epeirogenic movements which are here covered by the phrase, ordinary diastrophism. The stresses that arise within the continents simply because they protrude above the ocean beds are of a much more special and limited class. These stresses depend simply on gravity acting on the protruding matter as such without regard to other conditions; they are strictly inevitable and in the main independent. If the base on which the continents rest were absolutely inflexible, lateral stresses would arise within the continents from their gravitative pressures on their own masses, just as such stresses arise in continental glaciers and actuate them. If, on the other hand, the continents floated on a molten interior, or were in any other way kept in a continuous state of isostatic adjustment—in the usual sense of isostasy in which each column equals every other column in radial pressure—there would still arise within the protuberances unbalanced *lateral* stresses in proportion to the degree of protrusion.

It is perhaps necessary to remark here for the sake of complete clearness that isostasy, in the most complete and unlimited sense of the term, involves equal pressures in *all* directions, not merely equal pressures in vertical directions. Equal pressures in all directions are predicable only of perfect fluids. In this radical sense, the earth cannot be in complete isostatic adjustment at the present time because of its inequalities of surface and because of the differences in the lateral distribution of specific gravity in its crust, even if every vertical column balances every other vertical column perfectly. If the earth were ever in a complete

molten state—a view I do not now entertain—it would no doubt have assumed a state in which the lateral pressures would have been strictly equal and the vertical pressures also equal at any given depth, though of course varying with depth. The isostatic conditions would doubtless then have been complete and perfect in this radical sense, if we neglect such modifications as might have arisen from convection and similar internal disturbing activities. There should then have been a closely concentric arrangement of material according to its specific gravity, a uniformly level surface, and a universal ocean of uniform depth, as logically pictured by our geologic forefathers. This beautiful picture, were it true, would seem at first thought greatly to simplify the dynamic and diastrophic problems of the earth body, but in fact it forces upon us at once a problem of grave difficulty, the problem of finding a really rational way in which an earth, starting with such a symmetrical organization, could have passed into an earth with such irregularities of form and substance, and such differentiations of specific gravity as are actually presented by the existing earth. The depth to which the specific gravities of the continents and the sub-oceanic segments have recently been found to differ presents a new and formidable difficulty. The recent revival of the doctrine of isostasy, on the basis of geodetic data,[1] appears to have been regarded in some quarters as lending fresh support to the inherited view of a liquid earth, but in reality the results reached greatly augment a difficulty which had never been met with full success: the mode by which a horizontal differentiation of specific gravity in the outer part of the earth body could take place on a large scale, together with the mode by which the continental swells and the oceanic sags could be initiated and maintained. These great inequalities can be sustained only by adequate powers of resistance to the lateral stresses that tend to equate them and must always have tended to equate them. How such differentiations could have been forced upon a globe once in a fluidal condition—from which these

[1] The "Figure of the Earth and Isostasy from Measurements in the U.S. Coast and Geodetic Survey," Washington, D.C., 1909, and other papers of John F. Hayford; see also G. S. Burrard, "On the Origin of the Himalaya Mountains, a Consideration of the Geodetic Evidence," *Prof. Paper No. 12*, *Survey of India*, Calcutta, 1912; also *Geol. Mag.* Dec. V, Vol. X, No. 9 (September, 1913), pp. 385–88.

differentiations were necessarily absent—against the great stress-differences involved, is an obdurate problem that now takes on a new and definite aspect because of the very considerable depth to which the differentiation of specific gravity is found to extend. This, however, is not a problem to be discussed here; its solution is the task of those who entertain the view of the former fluency of the earth. The question is serviceable here by way of giving emphasis to the lateral stresses that inevitably exist in a protruding continental body due to its own gravity. If the continents were instantly converted into a molten condition they would flow at once and with violence toward an isostatic state and give a catastrophic illustration of the difference between the present state and a complete isostatic state.

The nature and the intensity of the lateral stresses in the continental protuberances may be easily visualized by means of an analytical picture of the continents and the great basins. Let these be assumed to be in isostatic equilibrium in the limited sense of the term as commonly used and let the protuberances be divided into independent vertical prisms of uniform dimensions. Then, if we choose to take the isostatic flotation view, each prism will float freely at a height inversely proportionate to its specific gravity, assumed to be the present height; or, if we prefer the solid isostatic view, each prism exerts the same pressure as each other prism on its base at the level of compensation. If the prisms be viewed as independent of one another, they must be sustained against the tendency to spread and collapse under their own gravity by a rigid coherent force acting transversely and equal at each point to the gravitative pressure at that point. This pressure is easily computed. If for this purpose we take the very conservative reliefs of 6,000 feet for the summit swells of the continents and of 12,000 feet for the bed of the ocean, the relief-difference will be 18,000 feet. This is not half the extreme actual differences but may perhaps fairly represent the continents if they were reduced to symmetrical swells. If we assume a specific gravity of 2.7 for continental rock, the gravitative pressure of the base of a prism rising from the horizon of the ocean bed to the border of the continents at sea-level, 12,000 feet, would not be far from 14,000 pounds to

the square inch. Over against this would be the pressure of 12,000 feet of water or roundly 5,000 pounds to the square inch, leaving a differential pressure of 9,000 pounds to the square inch, which may be taken as representing the pressure at the base of the border prisms of the continent. The prisms that would form the summits of the continental swells, taken at 6,000 feet above the sea-level, would suffer a differential pressure of about 16,000 pounds per square inch at their bases. Now unbalanced pressures of 9,000 to 16,000 pounds per square inch are equal to the crushing strength of weak rock and approach that of average rock. Oblique or transverse shearing would not unlikely take place in a prism of rock instead of crushing and this would require appreciably less stress, but just how much less has not been well determined as yet, so far as I know. There would be, at any rate, at the base of each such ideal prism of the continents, internal stresses that would approach the average strength of the rock of which they were composed and, in the weaker cases, would probably exceed it.

If now, instead of our idealized continental swells, we take the actual case, the stresses will be found much more intense. For example, the present Tibetan plateau over a wide area has an elevation of 15,000 feet or more above the sea-level, and the ocean bed, not far away, is considerably more than 12,000 feet in depth, so that after allowing for the oceanic pressure, there would be at the base of a Tibetan prism an unbalanced lateral pressure of 25,000 or 30,000 pounds to the square inch. In an isolated column this would be opposed only by the rigidity of the rock, and if this were of the average type, creep would certainly take place in the lower portion, if crushing did not anticipate it. The phenomenon of creep in mines and canyons under much less pressure leaves no room for doubt on this point.

But massed as the ideal prisms actually are in the continents, and surrounded by low slopes running out under the edges of the oceans, the actual case presents a modified aspect. The prisms not only lend some support to one another—though they must then carry one another's burden in some degree—but the sub-marine continental slopes buttress them. These buttresses are subject to lateral pressures of their own, but in so far as these pressures

fall below the creep pressure the residue of the strength of the buttresses opposes continental creep. The s. -oceanic buttressing is subject to further qualifications whose natures are more or less uncertain. The substructure of the border slopes of the continents is unknown. To some geologists, the preferred picture of the continental borders is that of fault scarps with slopes of incoherent sediment banked against these. To others, it is that of warps or folds of indurated rock below with sheets of recent sediments above and banks of recent sediments on their outer borders. To still others, the picture is that of a graduated sedimentary series, soft and incoherent at the surface and on the abysmal face, grading downward and backward into more and more indurated rock. This may or may not be more or less warped and compressed by thrusts from the ocean bed, according to situation. There are no doubt other conceptions. The continental borders present a suggestive field for study which has not yet been adequately cultivated.[1] It would be a diversion from our main purpose to enter into a discussion of the details of the continental borders here, but, though opinions are diverse in other respects, they are at one on two features that bear on this discussion: (1) some notable portion of the border material is soft and feebly coherent, and (2) the borders of the continents have been specially subject to deformative processes throughout geological history and were hence probably weakened in their resisting powers thereby through the development of shear planes. There is good reason to believe also that creep takes place in the more recent soft material, whatever may be true of the indurated parts of the continental protuberance as a whole.[2] These considerations make it difficult to judge how far the buttressing of the continents by the border slopes is effective in resisting the lateral pressure that tends to spread the protruding masses.

There is another consideration that affects the degree of resistance to lateral spreading in a possibly important way. It seems clear from an inspection of the folds of mountains that they are relatively superficial.[3] It is probable that a shear zone has been

[1] For some suggestions see Chamberlin and Salisbury, *Geology*, III (1906), 523–29.

[2] *Ibid.*, pp. 527–28.

[3] *Ibid.*, II, 128.

developed beneath the shell when it has suffered orogenic movements and that this facilitated folding and at the same time tended to limit it below. The shear is probably distributive through some depth and covers the horizons at which the tendency to creep is chiefly felt. The shear planes thus formed by the forceful orogenic agencies may serve as planes of movement for the less forceful creep afterward. The occasion for creep springs in some part from the elevation involved in the folding and allied diastrophic processes, and the creep itself is of the nature of a reversal of the elevating process, and so it may not unnaturally be facilitated by the shear planes already developed by the antecedent diastrophism.

Complicated by these modifying factors whose values are uncertain, it does not appear that the problem of creep is at present susceptible of satisfactory computative treatment; it can be dealt with now only in a naturalistic way on the basis of the evidence and the probabilities of the case. In time, when suitable geodetic surveys shall have been repeated, there will come positive demonstration. The creep movement, if it is appreciable, must result in a spreading of the geodetic stations, and exact measurements after sufficient intervals will give unequivocal evidence of the movement or of its absence, as also of its nature and its rate. Some few first steps in this direction have already been taken; notably the geodetic re-survey of the region of the recent California earthquake. Horizontal strain followed by horizontal movement were there shown, but they were too limited and their interpretation too uncertain to contribute much to the general question of creep. The demonstration that the movement was horizontal is, so far forth, favorable. The recognition that this and certain other earthquakes were due to differential horizontal movements—in distinction from the vertical movements to which earthquakes have generally been referred—is perhaps a step toward the demonstration of a wider system of horizontal movements of secular prevalence.

It would be going too far from our immediate purpose to set forth in full the phenomena that seem to point to glacier-like continental creep as one of the prevailing movements of the earth's crust. We are here merely seeking its possible effects on sea-transgressions and the stratigraphic terranes dependent on these.

The nearly universal presence of gaping crevices over the whole face of the continents, affecting all classes of rocks, is quite in harmony with a general spreading movement and has not otherwise found an altogether satisfactory explanation. Supporting this also is the prevalence of tensional faulting to so great a degree that it has gained the name *normal* faulting.[1]

It can hardly be supposed that such lateral stresses as must exist within the continents from the nature of the case, can fail to produce some effect, since changes of various sorts are going on within the continents, particularly molecular changes stimulated by heat, pressure, and other forces, and these must be influenced by the lines of least resistance imposed by the differential stresses. The vital question is whether this is a matter of geologic consequence or not. We must apparently wait for a decisive answer, and in the meantime treat the possibility of effective creep hypothetically.

The point of special interest in this discussion is the bearing which the hypothetical glacier-like creep of the continents has on such an adjustment of the land surface to the sea-surface as promotes systematic shelf-building and the development of shelf-seas as set forth in Article II of this series. We have found that ordinary diastrophic movements are, in the main, inimical to the close adjustments required. Continental creep is, however, regarded as essentially independent of ordinary orogenetic or epeirogenetic diastrophism; indeed it is regarded as, in a sense, their reversal. Its action is suspended or overwhelmed by movements in the opposite direction when a diastrophic revolution is in progress. It is only when ordinary diastrophism is quiescent and the continents are in their relatively static stages that the slow, gentle reactionary movement of creep is presumed to be appreciable.

Now this is not so much a vertical movement as a horizontal one, though actuated by gravity. It is indeed downward in a degree but it is horizontal in its main expression. By reason of this, it is fitted to become a copartner with gradation in leveling the land and thus facilitating an advance of the sea. It is in itself a massive form of gradation; it works toward a base-level of its

[1] For a discussion of creep in relation to faulting, see T. C. Chamberlin, "The Fault Problem," *Economic Geology*, II, No. 8 (1907), 709–21.

own. While I think its molecular methods are distinctly different from those of a true plastic body, the result is a continental spreading out and flattening down whose aspect is almost identical with that of a plastic body. A block of asphaltum will spread and flatten for years but it finally reaches a state beyond which the movement will not go. It reaches a base-level of a certain sort. So the continents, under the action of glacier-like creep, however great its efficiency may be supposed to be, will merely flatten out to a certain extent and the resulting surface will ideally be of the nature of a sloping plain closely analogous to the peneplain produced by erosive degradation.

So far as creep may be supposed to affect the continental shelf it moves it outward and slightly downward, and this fits the shelf surface for the reception of more sediments. If the downward component of the movement were greatly in excess of the rate of sedimentation, it would carry the shelf out of good working adjustment, much as in the case of ordinary diastrophism, but it seems highly improbable that the creep movement depresses the surface of the continental shelf faster than sedimentation naturally builds it up, even when the general continental creep is supplemented by the special creep in the soft sediments of which the younger upper and outer portions of the shelf are formed. The work of creep in thus pushing the shelf outward and slightly downward relieves wave-action of a part of its burden in building out the shelf and so enhances the joint effect. It seems safe therefore to regard creep as a co-operating adjunct to both parts of the gradational work, the leveling of the lands and the building-out of the shelves.

The outward creep of the continents reduces the capacity of the ocean basins and thus aids in lifting the sea-level and forcing the waters to creep out upon the lowered land. In this way also it co-operates with erosive gradation, which by transferring a portion of the land to the sea in another way raises the sea-level and causes its advance on the land.

While the great sea-transgressions—and the great terranes of parallel strata to which they gave rise—imply a relative freedom from diastrophism while forming, the details of bedding and

faunal distribution give evidence of minor oscillations, of advances and retreats of the sea, of shiftings of outlines, and of changes of barriers and connections, the effect of which is to introduce special features in the sedimentation and local or regional variations in the faunas. These features were subordinate to the grander deployments both in area and in time, and in this subordination they suggest that they may have been due to minor and perhaps separate agencies that acted more continuously and in smaller units—more easily and variously shifted—than the profound deformative agencies that were liable to interrupt the whole process. Gentler agencies whose general activities were harmonious with the main sedimentary process seem better fitted for this function than a supposed feeble action of a titanic agency whose normal action would put an end to the whole process.

There is an aspect of continental creep, if we may follow the analogy of glaciers, that seems to fit it for this function. The suggestion is at least worth entertaining and testing as a working hypothesis. The creeping body of a glacier does not always decline steadily in the direction of its motion but rather assumes a more or less undulatory mode of progress. While the advancing surface, taken as a whole, slopes forward, it may, in a subordinate measure, slope backward, i.e., *rise* in the direction of its advance. On broad glaciers of nearly flat surfaces, there are sometimes swells and sags; the surface water sometimes gathers into lakelets, and occasionally streamlets of notable size flow in a direction *opposite* to the flow of the glacier beneath.[1] These anomalies are assignable to irregularities in the rock floor over which the ice mass is thrust by its internal stresses. The creep of a continental embossment, if it follows the glacial analogy, may be assigned a similar undulatory mode of progress. If continental creep is facilitated by a shear zone that had been formed previously by the powerful stresses that actuated the lateral crust movements of earlier times, the shear planes of the zone are not probably perfectly plane; they are much more probably undulatory, for the surface effects of the diastro-

[1] See T. C. Chamberlin, "Glacial Studies in Greenland," *Jour. Geol.*, II (1894), 784, Fig. 12, view of a portion of Blase Dale Glacier showing the undulation of its surface involving a backward inclination. For a backward flowing stream see Vol. V (1897), 231–32.

phism and probably the basal effects were undulatory. The glacier-like rock mass in being thrust by its own internal stresses over these undulatory shear planes—in effect an undulatory floor like that of the glacier—must probably have gently swelled and sagged as does ice under similar conditions. The sea, or any other water-body, lying upon this creeping undulating sheet would suffer shiftings of outline, changes of deposition, rises and removals of barriers, attended by variations of faunal development. While these might rise to some moment, and might seem to be epeirogenic in nature, they would not usually suspend the main progress of sea-transgression, but rather, on the whole, be tributary to it, whatever their temporary or local effect might be. If this source of minor oscillations shall ultimately find warrant, it will relieve us of referring these various slight intercurrent undulations of the surface to those deep-seated potent agencies whose normal action is refractory rather than compliant with the gradational agencies on whose well-adjusted action the development of the great stratigraphic terranes, as a whole, are dependent.